# CP Violating Top Yukawa at a Multi TeV Muon Collider

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# Muon Colliders

- Why consider a muon collider?
  - cleaner collision environment compared to proton-proton collisions
  - high energy achievability compared to electron-positron collider
  - smaller energy loss due to synchrotron radiation

- Disadvantages:
  - muon decay
  - easily obtained, but difficulties with collimation



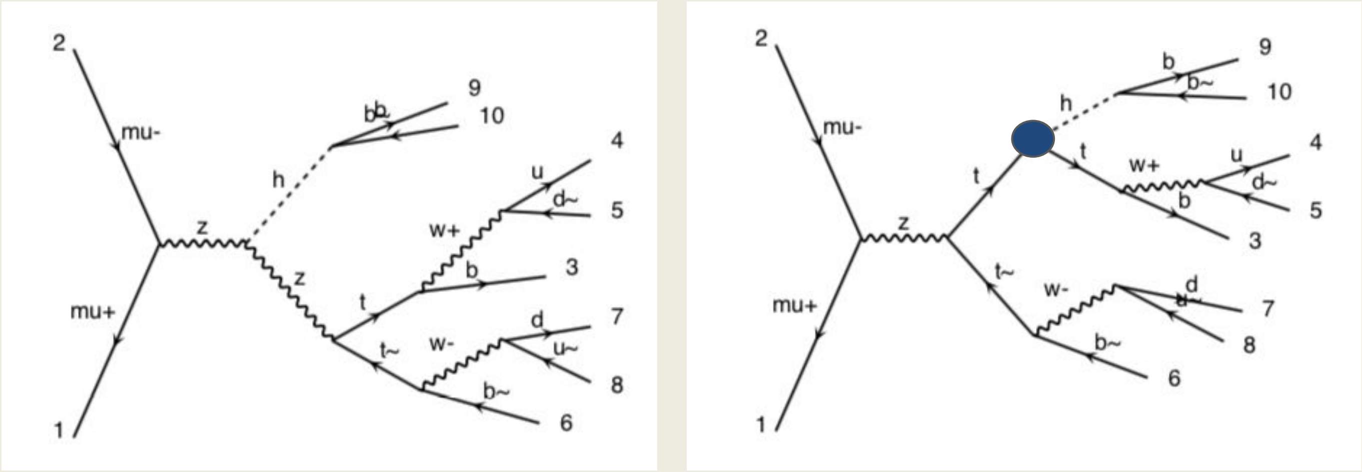
Detector and Physics Performance at a Muon Collider, Nazar Bartosik et. al, https://arxiv.org/abs/2001.04431

# Top Yukawa Coupling

- Aim to explore CP tth violating coupling via tth, tth$\nu\nu$ ,and tbh$\mu\nu$. The tth interaction Lagrangian term modeled by:

$$\mathcal{L} = -\frac{m_t}{v}\kappa_t \bar{t}(cos\alpha + i\gamma_5 sin\alpha)th$$

- alpha is the CP violating phase, kappa coupling strength
- Current constraints according to ATLAS: $|\alpha| \lesssim 43°$

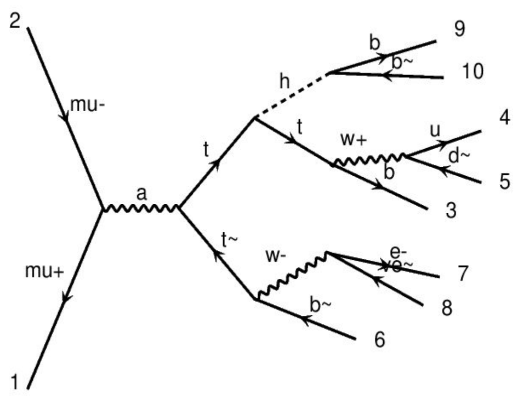


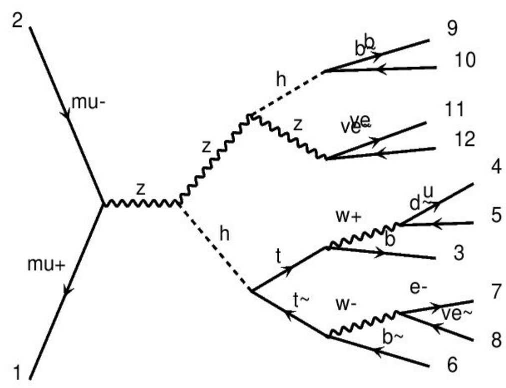

Representative Feynman diagrams for signal process tth with decay. The left diagram does not contain tth coupling. The right diagram tth coupling is marked in red.

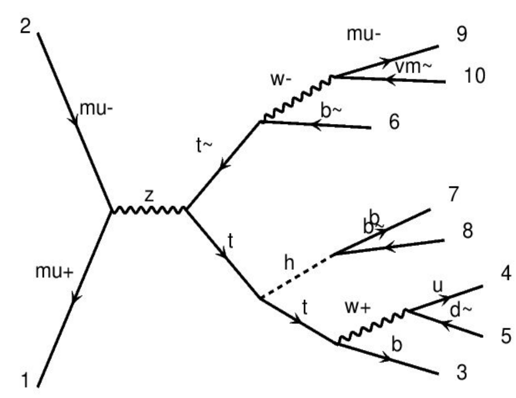
# Signals

1. $\mu^+\mu^- \to t\bar{t}h$
2. $\mu^+\mu^- \to t\bar{t}h\nu\bar{\nu}$
3. $\mu^+\mu^- \to t\bar{b}h\mu^-\bar{\nu}$

$$t \to bW^+, W^+ \to jj$$
$$\bar{t} \to \bar{b}W^-, W^- \to \ell^-\bar{\nu}_\ell$$
$$h \to b\bar{b}$$



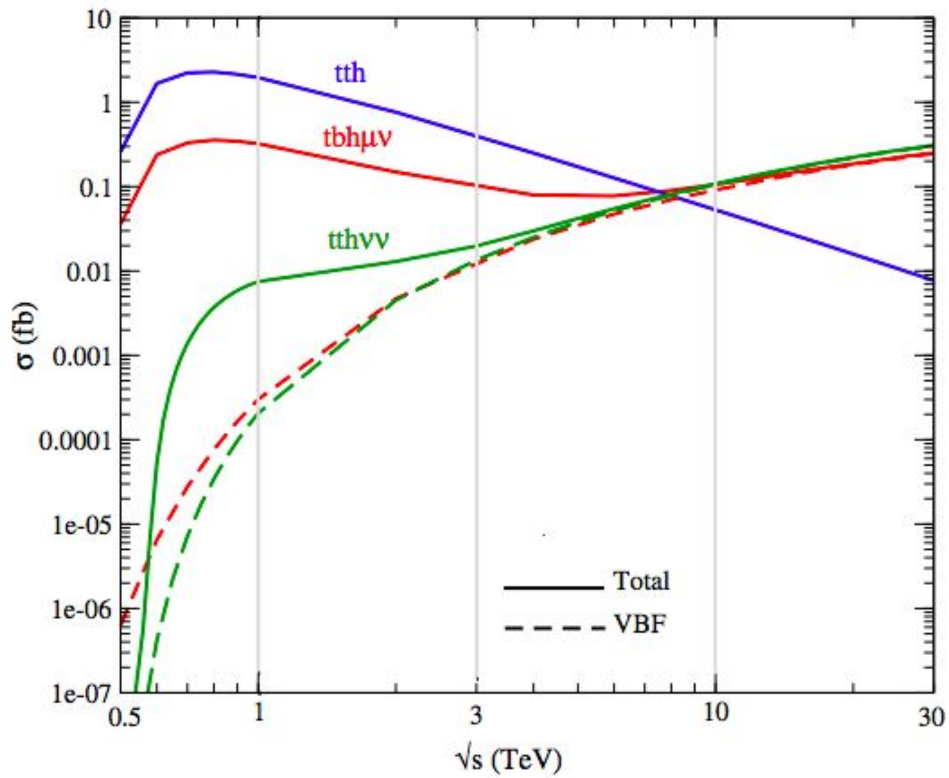



# Cross Section versus √s for the Standard Model

- cross section versus c.o.m. energy from 500 GeV to 30 TeV for signals:

$$\mu^+\mu^- \to t\bar{t}h$$
$$\mu^+\mu^- \to t\bar{t}h\nu_\ell\bar{\nu}_\ell$$
$$\mu^+\mu^- \to tbh\mu\nu$$

- All processes generated through MadGraph5_aMC@NLO.



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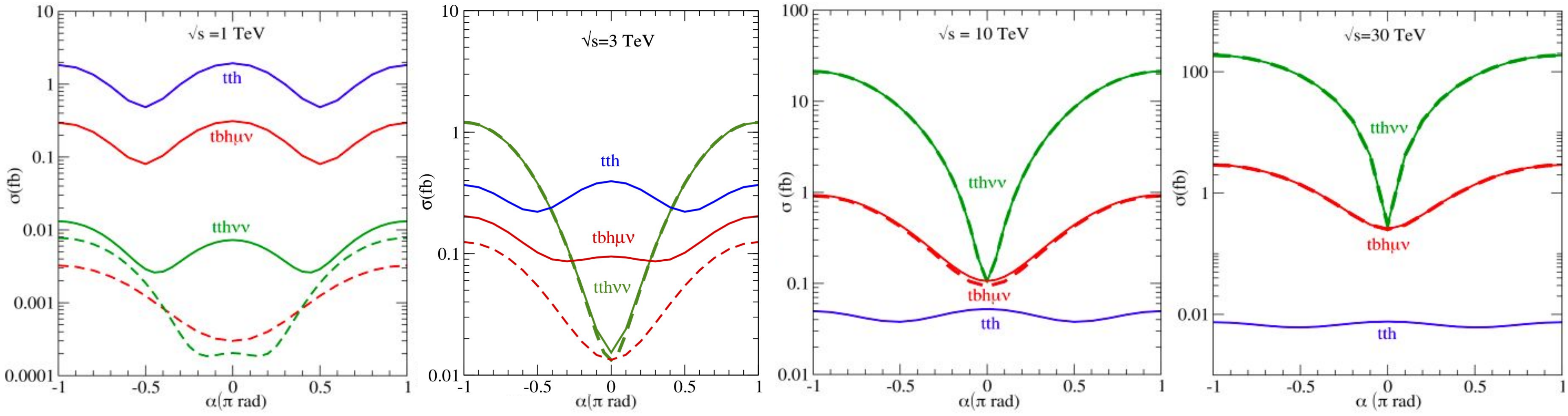
# Cross Section versus CP Phase




- Cross section varying with cp phase from -$\pi$ to $\pi$ for signal processes at 1, 3, 10 and 30 TeV. Dashed lines show VBF contributions for tth$\nu\nu$ and tbh$\mu\nu$.
- Cross section sensitive to CP phase at high energies

# Benchmark Luminosities

- Using an estimated cross section at 10 TeV of 1 fb

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left( \frac{\sqrt{s}_\mu}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

| $\sqrt{s} \quad (TeV)$ | $L \quad (fb^{-1})$ |
|---|---|
| 1 | 100 |
| 3 | 1000 |
| 10 | 10,000 |
| 30 | 10,000 |

**Table**: Corresponding luminosities for each of the four benchmark energies.



Muon Colliders, Jean Pierre Delahaye et. al, https://arxiv.org/pdf/1901.06150.pdf
Snowmass, muon forum, https://snowmass21.org/energy/muon_forum

# $2\sigma$ Exclusion & $5\sigma$ Discovery

- Log likelihood ratio used to determine $5\sigma$ discovery and $2\sigma$ exclusion.
- Likelihood function following Poisson distribution: $L(x|n) = \frac{x^n}{n!}e^{-x}$

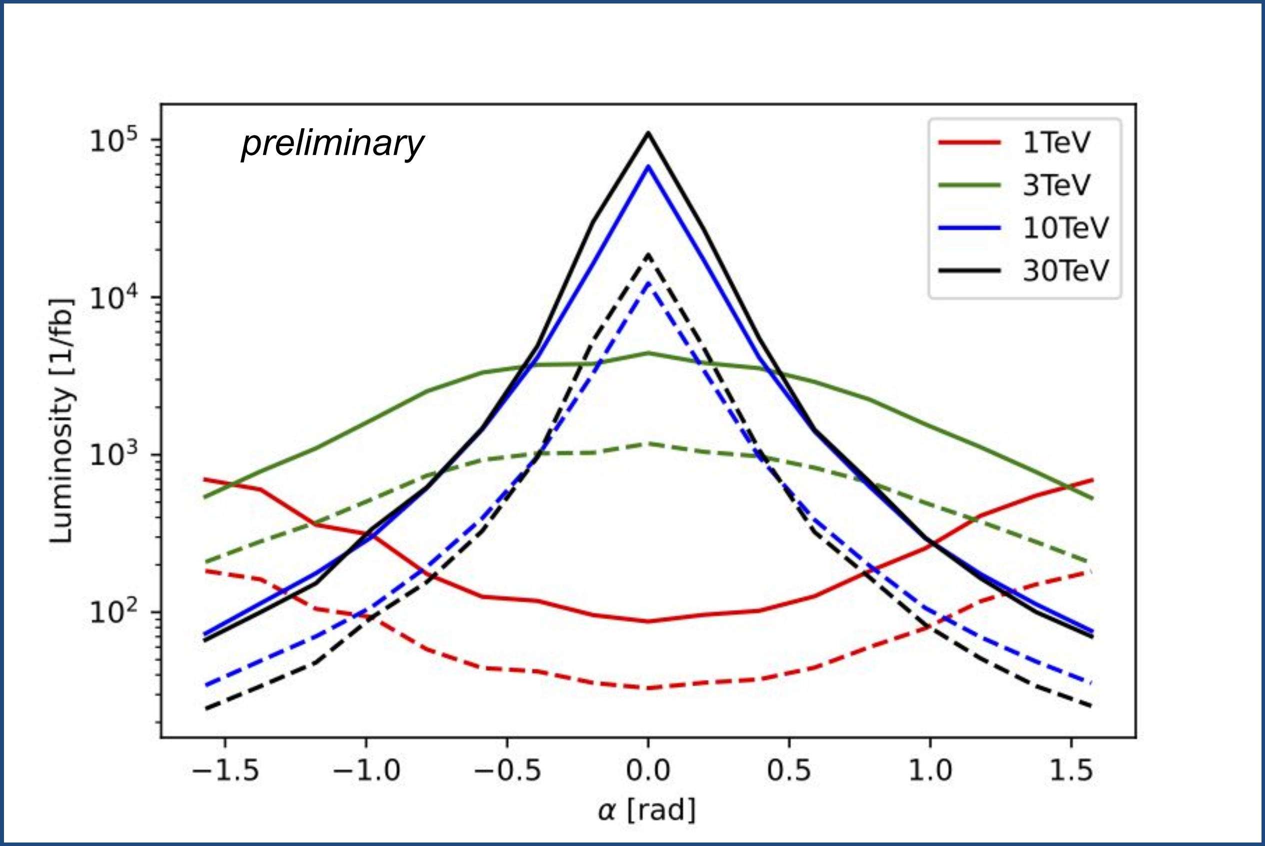
$$\sigma_{dis} \equiv \sqrt{-2\ \ln\left(\frac{L(B|Sig+B)}{L(Sig+B|Sig+B)}\right)}$$

$$\sigma_{exc} \equiv \sqrt{-2\ \ln\left(\frac{L(Sig+B|B)}{L(B|B)}\right)}$$

**Top:** formula used to calculate $5\sigma$ significance

**Bottom:** formula used to calculate $2\sigma$ significance

# Luminosity versus CP phase




**Solid Lines:**
Corresponding luminosity required to achieve $5\sigma$ discovery for a particular $\alpha$ value.

**Dashed Lines:**
Luminosity required for $2\sigma$ exclusion of particular $\alpha$ value.

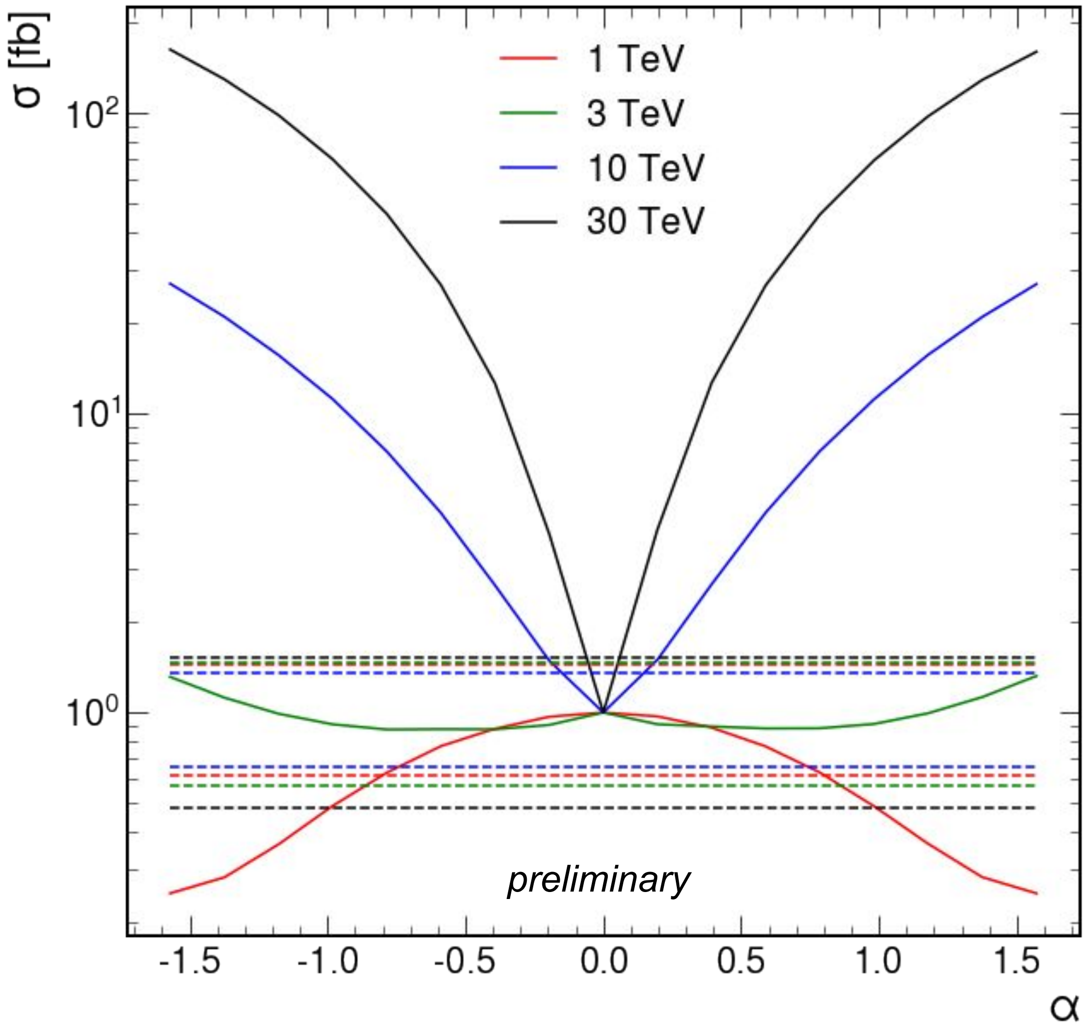
# $2\sigma$ Exclusion on CP phase

Bands give $2\sigma$ exclusion on $\alpha$ using benchmark luminosities.
-5% systematics

**Solid Lines:**
Combined signal cross section before cuts normalized to SM.
**Dashed Bands:**
Projected bounds at 95% CL normalized to SM.

Approximate values:
$|\alpha| \lesssim 47°$ at 1 TeV
$|\alpha| \lesssim 9°$ at 10 TeV
$|\alpha| \lesssim 3°$ at 30 TeV

3 TeV relatively independent



# $2\sigma$ Exclusion on CP phase cont.

| $\alpha$ bounds at 95% CL | Channel | Collider |
|---|---|---|
| $\lvert\alpha\rvert \lesssim 36°$ | $dileptonic\ \ t\bar{t}(h \to b\bar{b})$ | HL -LHC |
| $\lvert\alpha\rvert \lesssim 25°$ | $t\bar{t}(h \to \gamma\gamma)\ \ combination$ | HL-LHC |
| $\lvert\alpha\rvert \lesssim 3°$ | $dileptonic\ \ t\bar{t}(h \to b\bar{b})$ | 100 TeV FCC |
| $\lvert\alpha\rvert \lesssim 9°$ | $semileptonic\ \ t\bar{t}(h \to b\bar{b})$ | 10 TeV muon collider |
| $\lvert\alpha\rvert \lesssim 3°$ | $semileptonic\ \ t\bar{t}(h \to b\bar{b})$ | 30 TeV muon collider |

**Table**: bounds at 95% CL for $\alpha$ at different colliders.



Directly Probing the CP-structure of the Higgs-Top Yukawa at HL-LHC and Future Colliders
R. K. Barman, et.al .http://arxiv.org/abs/2203.08127

# Conclusion

- Muon collider new type of lepton collider with advantages  and trade-offs
- Studying processes ( tth, tth$\nu\nu$, tbh$\mu\nu$) with CP violating top-Higgs coupling at a muon collider
- Due to VFB,  tth$\nu\nu$ is dominate signal at high energies
- Cross section sensitive to magnitude of CP Phase

# Questions?

# Backups

# Cross Section Parameterization for tth$\nu\nu$

- Can parameterize $\sigma$ to understand dependence on $\alpha$:

$$\sigma_{t\bar{t}h\bar{\nu}\nu}(\alpha) = C^4 cos^4\alpha + C^3 cos^3\alpha + C^2 cos^2\alpha + C^1 cos\alpha + C^0$$

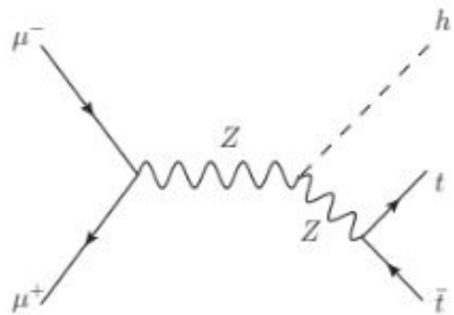
| | $t\bar{t}h\nu\bar{\nu}$ | | | |
|---|---|---|---|---|
| $\sqrt{s}$ (TeV) | 1 | 3 | 10 | 30 |
| $C^4$ | $-1.35 \cdot 10^{-4}$ | $-4.41 \cdot 10^{-3}$ | 0.019 | $-0.43$ |
| $C^3$ | $7.04 \cdot 10^{-5}$ | $-0.013$ | $-0.17$ | $-0.13$ |
| $C^2$ | $7.44 \cdot 10^{-3}$ | 0.24 | 2.16 | 8.09 |
| $C^1$ | $-3.00 \cdot 10^{-3}$ | -0.58 | $-10.43$ | $-93.23$ |
| $C^0$ | $2.89 \cdot 10^{-3}$ | 0.38 | 8.53 | 86.00 |

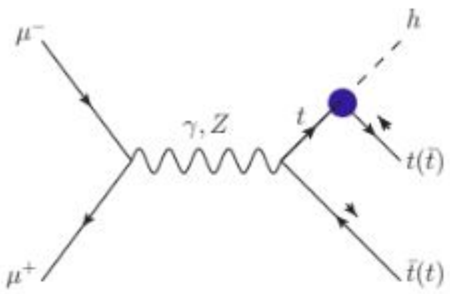
- for fixed √s can determine which type of diagram dominates
- For the SM value, $\alpha$ = 0, have large destructive interference.
- $\alpha = \pi$, becomes constructive.

# tth diagrams

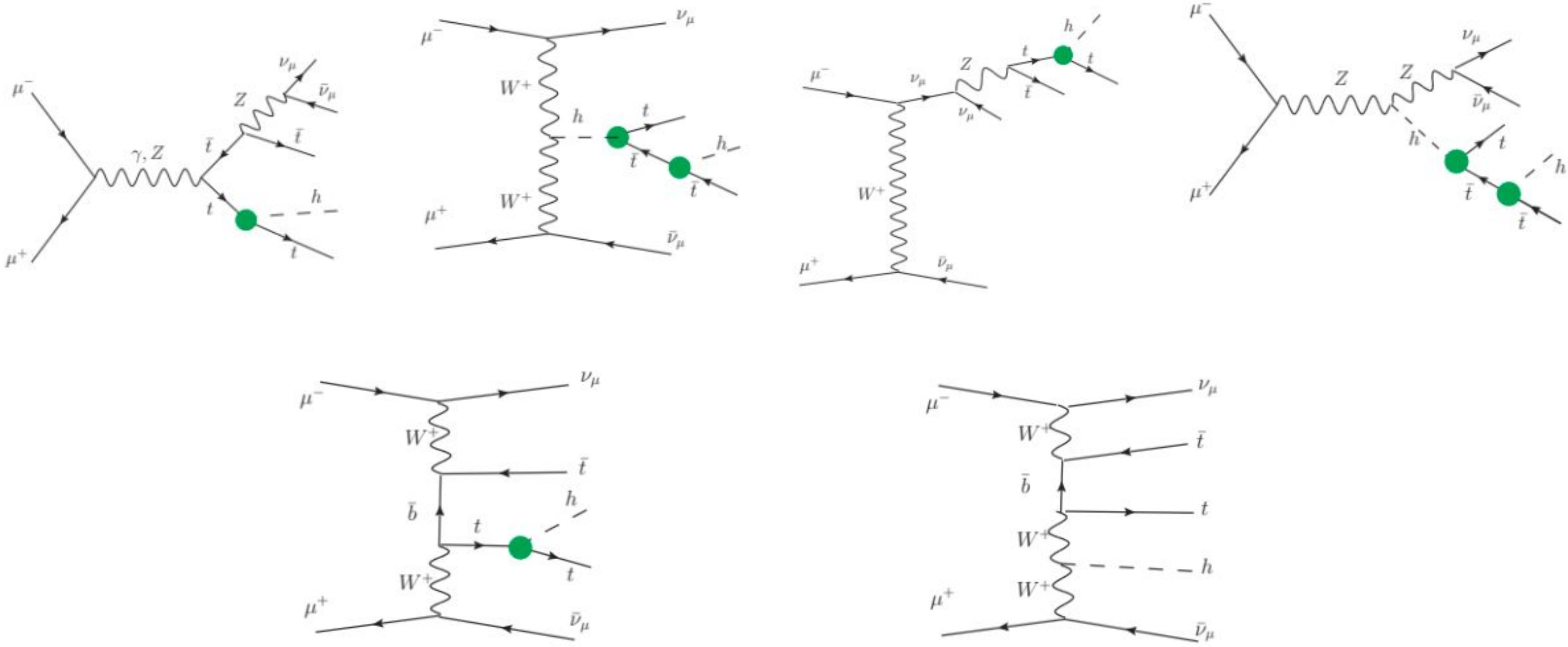
- Can parameterize tth cross section as:

$$\sigma_{t\bar{t}h}(\alpha) = C^2 cos^2\alpha + C^1 cos\alpha + C^0$$



# tth$\nu\nu$ diagrams



# tbh$\mu\nu$ diagrams